

THE INTERPLAY OF ULTRAHIGH-ENERGY COSMIC RAYS AND EXTRA DIMENSIONS

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Abstract

Regarding ultrahigh-energy cosmic rays (UHECRs) as a probe and extra dimensions as a possible ingredient of the fantastic ultrahigh-energy world, we discuss possible interplay between them. On the one hand small extra dimensions and Kaluza-Klein bursts present a feasible way to the origin of UHECRs. On the other hand large extra dimensions may change various interactions between particles at ultrahigh energies and therefore impact on air showers created by UHECRs. Conversely, UHECR data may tell us secrets veiled in extra dimensions.

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1 Introduction

The detection of ultrahigh-energy cosmic rays (UHECRs) of energies above 10^{19} eV, especially super-GZK (Greisen-Zatsepin-Kuzmin) events, entails various unsolved puzzles and accordingly brings us serious challenges of understanding UHECRs: their origins, compositions, unusual largeness of energy, distribution of arrival directions and times, interactions with background particles or fields along the journey to the earth, interactions with the atmosphere and showers generated thereof, and detection methods. UHECRs are more mysterious under the GZK mechanism [1], which may lead to the GZK cutoff in the spectrum, as to be explained later. There is a controversy about the GZK cutoff: AGASA data show no cutoff [2], while HiRes data admit a cutoff in spectrum around 10^{20} eV [3]. (For a review, see [4].)

The GZK mechanism is an energy degrading process in the journey of ultrahigh-energy particles through the universe, caused by the interactions with background particles or fields such as background photons γ [cosmic microwave background (CMB), radio background (RB) and infrared background (IRB)], relic neutrinos ν_{CMB} , or cosmic magnetic fields B. In the following we list the attenuation lengths of various particles of energy 10^{20} eV: (in unit of Mpc)

$p + \gamma_{\text{CMB}}$	$N + \gamma_{\text{CMB,IRB}}$	$\gamma + \gamma_{\text{CMB,RB}}$	$e + \gamma_{\text{CMB,RB}}$	$e + B$	$\nu + \nu_{\text{CMB}}$
100 Mpc	10 Mpc	10–100 Mpc	6–13 Mpc	2–100 Mpc	$\gg 100$ Mpc

where p, N, e, and ν stand for proton, nuclei, electron, and neutrino, respectively.

2 Theoretical Challenges from Ultrahigh-Energy Cosmic Rays

Ultrahigh energies and isotropic arrival directions in the observational results, together with the GZK mechanism, pose the main challenges for UHECR models, which are usually divided into bottom-up and top-down models. In the following we discuss the difficulties of explaining UHECRs in these two categories of models.

2.1 Bottom-up Models

In bottom-up models (for a review, see [5, 6]), particles are accelerated to ultrahigh energies within extreme astrophysical environments, such as cluster shocks, active galactic nuclei, neutron stars, and maybe some environment associated with gamma-ray bursts. Usually these extreme environments are very dense. How ultrahigh-energy particles escape from these dense regions without losing much energy through the scattering with particles therein is a serious intrinsic problem.

In addition, most of particles under the GZK mechanism cannot maintain energies beyond the GZK threshold (around 10^{20} eV) after travelling a distance longer than about 50 Mpc, so that it is unlikely for UHECR sources to be located outside the GZK zone, a region with a radius of about 50 Mpc around the earth. Unfortunately, there are very few powerful enough sources within the GZK zone. These few sources can hardly explain UHECR data, in particular, the spectrum and the distribution of arrival directions.

2.2 Top-Down Models

In top-down models (for a review, see [5]), UHECRs are produced via decays of very massive particles (or topological defects) that may be relics of the early universe. Therefore energy is not an issue as long as the mass is large enough. These very massive relic particles might behave like dark matter and reside in the local dark halo, waiting for decays that generate UHECRs reaching us. In this case, the roughly isotropic distribution of arrival directions is not an issue, either. Nevertheless, these very massive particles are exotic, i.e., they are beyond the standard model of particle physics. Their unconfirmed existence is an essential problem in this kind of models.

In addition, many top-down models involve QCD fragmentation in the production of UHECRs. UHECRs originating from such fragmentation are mostly photons and neutrinos, which seem to be disfavored by present data. However, whether photons or neutrinos can be UHECR primaries is still not concluded.

3 Interplay of UHECRs and Extra Dimensions

So long as UHECR observations have opened the door to understanding the unknown ultrahigh-energy world, we consider a possible essential ingredient in this fantastic world, extra (spatial) dimensions, whose existence is required by various theories beyond the standard model, especially in the theories for unifying gravity and other forces, such as superstring theory.

3.1 Small Extra Dimension: Kaluza-Klein Burst

Recently a new mechanism for generating UHECRs, by employing small extra dimensions as a perfect bearer of large energies, is proposed [7]. In this model UHECRs are generated via Kaluza-Klein (KK) bursts, a violent energy transfer from extra dimensions to ordinary dimensions through collisions between KK modes.

With the benefit of various features of small extra dimensions, many difficulties in UHECR models can be overcome, as outlined in the following. The violent energy transfer from extremely small extra dimensions to ordinary dimensions through KK bursts can easily reach required ultrahigh energies, thereby making it possible to construct top-down models without introducing new particle species. Against the energy pillage by the GZK mechanism, KK momentum conservation can protect the energy stored in extra dimensions when particles travel through the universe. This feature can help particles of large energies escape from the source without losing much energy and make it possible for UHECR sources (more exactly, sources of KK modes which generate UHECRs) to be located outside the GZK zone, thereby benefitting bottom-up models.

As shown in [7], clumped KK modes of sizes ranging from KK stellar compact objects to “KKONIUM”, a bound state consisting of KK modes, are possible origins of UHECRs. The energy density of these KK stellar compact objects should range from that of a white dwarf to a neutron star, and the size of KKONIUM should be around 10^{-6} cm or less, corresponding to the required size of extra dimensions, 10^{-27} – 10^{-25} cm. Small-scale clustering in arrival

directions and dispersion in arrival times of these clustering UHECR events are possible signatures of KK compact objects.

3.2 Large Extra Dimension

In the scenario of large extra dimensions, the cross section of interactions between various particles may be significantly changed due to the presence of KK towers of gravitons that mediate interactions. For example, ultrahigh-energy cosmic neutrinos when entering the atmosphere may produce black holes, increasing the neutrino-nucleon cross section and initiating air showers with a higher rate, thereby making neutrinos more qualified to be the UHECR primaries [8, 9, 10].

However, it is not good for bottom-up models. The same feature will make ultrahigh-energy particles even more difficult to escape from their sources without losing much energy, and therefore make bottom-up models more unlikely to work.

As a remark, the small and the large extra dimensions are not two contradictory aspects. Our world may possess both. In addition, in the scenario of large extra dimensions the small thickness of the brane can play the role of extremely small extra dimensions employed in [7].

4 Conclusion: an Opening of the Ultrahigh-Energy World

The detection of UHECRs have opened a window for the unknown ultrahigh-energy world. Regarding extra dimensions as a possible substantial ingredient in this world, there may be essential interplay between them. As suggested in [7], small extra dimensions and KK bursts present a feasible way to understanding the origin of UHECRs from both bottom-up and top-down viewpoints. In addition, large extra dimensions may modify the strength of various interactions and impact on air showers created by UHECRs. Conversely, the details of UHECRs may also provide important information (or constraints) about extra dimensions. Apparently, a great feast in the opening of this fantastic ultrahigh-energy world is coming soon.

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